Circular dichroism of chiral photonic crystals with enclosed defect layer inside

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ABSTRACT

The circular dicroism is calculated in a one-dimensional chiral soft matter (cholesteric liquid crystal) cells on the presence of an isotropic defect layer. The effects of absorption and gain on circular dichroism are investigated and it is shown that the subject system in some circumstances can work as a low threshold laser, a multi-position trigger, a total wide/narrow band absorber, or a wide/narrow band filter/mirror. This work demonstrates the effects of absorption and emission in photonic crystal layers, which offers a novel approach for understanding of tunable soft matter photonic materials.

Keywords: photonics, liquid crystals, circular dichroism, eigen polarizations, diffraction, transmission, photonic band gap

1 INTRODUCTION

In recent years, photonic crystals (PCs) consisting of artificial and self-organizing periodic structures, have attracted considerable interest due to the changes in their spatial dielectric/magnetic properties at the scale of the order of optical wavelengths [1,2]. This includes complex soft matter systems, namely, liquid crystals (LCs), molecular photonic crystals, and artificially synthesized or spontaneously self-organized micro- and nano-structures with interesting predetermined physical properties, wide potential for novel practical applications and functionalities. The optical element constructed on the basis of photonic crystals result in an intelligent, multifunctional tunable optics possesses with favorable traits such as compactness, small loss, high reliability and compatibility. To build new optical architectures with controlled absorption/emission processes, the accurate numerical design in the artificial and self-organizing periodic structures is necessary to display material properties and active chiral processes in PCs, biological liquid systems, including soft matter. In this context, CLCs hold great promise and opportunities in optics and photonics owing to their self-organized periodic (dielectric, magnetic) helical structure. Chirality is an important property used in biology, chemistry and pharmacology, since a significant proportion of molecules in these structures show functionalities determined by their chiral configuration. The soft matter nature of these materials and their response to external influences lead to readily tunable laser light. The broad wavelength tuning range of LC lasers, coupled with their microscopic size, narrow line widths (< 0.1 nm), and high optical efficiencies as compared with more conventional solid-state lasers, can provide novel applications in areas of medical diagnostics, holography, etc.

Cholesteric liquid crystals (CLCs) are the most representative among the one-dimensional (1D) chiral soft photonic crystals, since they can spontaneously self-organize periodic structured with induced polarization-sensitive photonic band gaps. Its location and width depend on the pitch parameter, *p*, as well as on the ordinary and extraordinary local refractive indices (i.e. on n_o and n_e, respectively) of the cholesteric material. The reflection band of CLCs is defined by the condition, $n_o p<\lambda<n_e p$. Within the photonic band gap the circularly polarized light, having the same handedness as the CLC helix, is reflected only selectively. The light polarized with the opposite handedness and that with the wavelengths outside the photonic band gap both are transmitted simultaneously through the CLC film.

CLCs with defects of various types in their structure have been recently considered in view of generating additional resonant modes in spectra and possibility of low threshold lasing on these modes [3-9]. Such defect modes localized in the defect positions can be used for the construction of tunable narrow band filters and mirrors. In contrast, to the ordinary PC, the excitation (defect) modes in CLCs have polarization peculiarities; they are either narrow transmittance lines in the photonic band gap of the incident light, or they are narrow lines of reflection in the transmittance band for diffracting and non diffracting circular polarization of the incident light, correspondingly. Intense studies in this field are underway.

Here we discuss the influence of absorption and gain on the circular dichroism for a CLC cell with an isotropic defect layer (Fig. 1).

2 RESULTS AND DISCUSSION

CLC layers with defect can be described by a multi-layer system: *CLC(1)-Defect Layer-CLC(2)* (Fig. 1). The problem was solved by the modified Ambartsumian's layer addition method [5,6]. The ordinary and extraordinary refractive indices of the CLC layer (with the thickness d_1=44p, where p is the CLC helix pitch) are taken to be: $n_o = \sqrt{\varepsilon_2} = 1.4639$ and $n_e = \sqrt{\varepsilon_1} = 1.5133$ (ε_1, ε_2 are the principal values of the local dielectric permittivity tensor of the CLC); the CLC layer helix is right handed and its pitch is: p = 420 nm. The right circularly polarized light normally incident onto a single CLC layer displays the presence of a photonic band gap (which is in the range of λ= 614.8 ÷ 635.6 nm), while the light with the left circular polarization (LCP) does not have any gap feature. The refraction coefficient, n, of the isotropic defect layers is chosen as: $n = \sqrt{\varepsilon} = 1.8$.

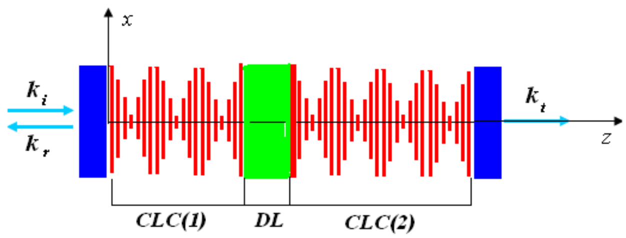

Fig. 1. A sketch diagram of a modelled CLC cell with a defect layer inside.

Circular dichroism in optically active material describes the differential absorption of the left- and right-handed circularly polarized light. The characteristic shape of circular dichroism spectra recorded from the molecules such as proteins or DNA – usually appearing in the ultraviolet range–reflects their chiral geometry and originates from the superposition of circular dichroic signals of many randomly oriented molecules in the liquid solution. CLC due to their chiral periodic structure in the scale of optical wavelength order provides a strong and characteristic circular dichroism response at visible wavelengths.

The circular dichroism is defined by the expression:

$$\Delta A = A^l - A^r, \qquad (1)$$

where the quantity, A=1–(R+T), characterizes the light energy absorbed by the system (R and T are the reflection and transmission coefficients, respectively) and $A^{l,r}$ are the light absorptions, if the incident light has left and right circular polarizations, respectively.

The circular dichroism spectra for the single homogeneous CLC layer (the pink solid line) and for the CLC layer with the isotropic defect layer inside (the red and blue solid lines) are presented in Fig 1. The solid line corresponds to $n_o'' = n_e'' = 0$ and $n'' = 0$, that is, when absorption is absent in the CLC sublayers and it exists in the defect layer. The dashed lines correspond to $n_o'' = n_e'' \neq 0$ and $n'' = 0$, that is, when absorption exists in the CLC sublayers and it is absent in the defect layer. The red lines correspond to the case when the defect mode wavelength is in the centre of the photonic band gap (d_2=2000 nm) and the blue lines correspond to the case when the defect mode wavelengths are near the boundaries of the photonic band gap (d_2=2100 nm). Here, we assume that absorption is constant, that is, it does not depend on the frequency for the presented effects connected with structural peculiarities of the subject system.

As it is seen in Fig. 2, ΔA is positive in the photonic band gap for the single homogeneous CLC layer and it is natural as the CLC layer helix is right handed; and for incident light with the right circular polarization total reflection takes place here and, therefore, here the suppression of absorption of light with the right circular polarization takes place, while the light with the left circular polarization is transmitted through the system undergoing large absorption. ΔA is negative outside of photonic band gap it is natural too, as the reduced distance of the light becomes more – due to the light diffraction interaction with the right circular polarization – than that with the left circular polarization. Consequently, $A^r > A^l$, here. If there is a defect in the structure of the medium, the circular dichroism can be positive, or zero, or less than the unit depending on the values of the parameters characterizing the system (the details see below).

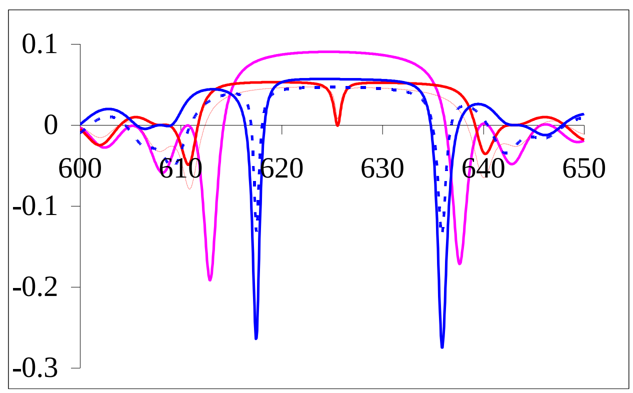

Fig. 2. The circular dichroism spectra for the single CLC layer (the pink solid line) and for the CLC layer with the isotropic layer defect inside (the red and blue lines). The red lines correspond to the case when the defect mode wavelength is in the centre of the photonic band gap (d_2=2000 nm) and the blue lines correspond to the case when the defect mode wavelengths are near the boundaries of the photonic band gap (d_2=2100 nm). $\mathrm{Im}\varepsilon_1 = \mathrm{Im}\varepsilon_1 = 0.0005, \mathrm{Im}\varepsilon = 0$ for the dashed lines and $\mathrm{Im}\varepsilon_1 = \mathrm{Im}\varepsilon_1 = 0, \mathrm{Im}\varepsilon = 0.005$ for the solid lines.

In Fig. 3 the dependence of the circular dichroism (ΔA) on the absorption parameter, $x = \ln(\mathrm{Im}\,\varepsilon_m)$, is presented for various defect layer thicknesses. As in Fig 2, the solid lines correspond to $n_o'' = n_e'' = 0$ and $n'' \neq 0$, and the dashed lines correspond to the case when $n_o'' = n_e'' \neq 0$ and $n'' = 0$. The red lines correspond to the case when the defect mode wavelength is in the centre of the photonic band gap (d_2=2000 nm) and the blue and pink lines correspond to the case when the defect mode wavelengths are near the boundaries of the photonic band gap (d_2=2100 nm and d_2=1900 nm, respectively). As it is seen in the figure, if $n_o'' = n_e'' \neq 0$ and $n'' = 0$, then the circular dichroism firstly decreases if the parameter x increases and after that, having a minimum, it begins to increase. After this, it achieves a maximum and then vanishes if x keeps increasing. The situation is different if $n_o'' = n_e'' = 0$ and $n'' \neq 0$. In this case the circular dichroism firstly decreases if the parameter x increases and, having a minimum, it tends to the unit if x keeps increasing. Note that the case when ΔA does not change its sign (the redlines) is special in the sense that such an effect is only observed for the system parameters when the defect mode wavelength is precisely in the center of the band gap.

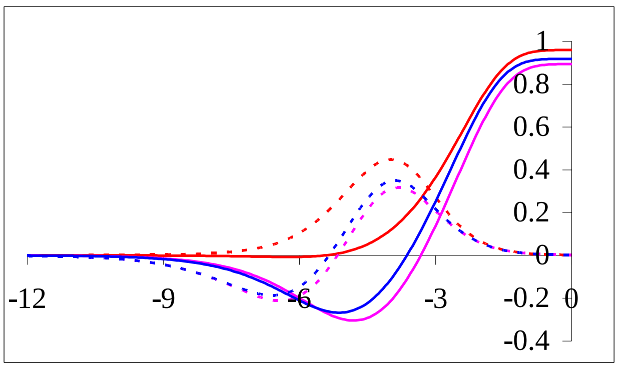

Fig 3. The circular dichroism (ΔA) versus the parameter, $x = \ln(\mathrm{Im}\,\varepsilon_m)$, characterizing the absorption at different values of the defect layer thickness.

To find out the presented circular dichroism peculiarities we investigate the dependences of the reflection (R), transmission (T) and absorption (A) versus x for the light incident both with right and left circular polarizations. In Fig. 4 these dependences are presented for various thicknesses of the defect layer. The analysis of the presented results in this figure shows that the presence of absorption worsens the connection between the two sublayers of the CLC and decreases the tunneling of the light through the optical barrier. If $n_o'' = n_e'' \neq 0$ and $n'' = 0$, that is, when absorption exists in the CLC sublayers and it is absent in the defect layer, the connection between the two sublayers of the CLC is worsened, if the parameter x increases, then the regime of the reflection from the whole system passes into the regime of reflection from the first sublayer of the CLC (provided x increases) therefore, the reflection begins to increase. If the parameter x keeps increasing, the reflection decreases as in the case from the single CLC layer if the absorption is essentially increased. In the case, $n_o'' = n_e'' = 0$ and $n'' \neq 0$, that is, when absorption is absent in the CLC sublayers and it exists in the defect layer, again, if the parameter x increases, then the regime of the reflection from the whole system passes into the regime of reflection from the first sublayer of the CLC (provided x increases) therefore, the reflection begins to increase. But as absorption in the sublayers of the CLC is absent, the further increase of x leads to worsening of the connection between the sublayers and the reflection is monotonously increasing due to the significant thickness of the first sublayer of the CLC, because it has the possibility to provide complete light reflection in the band gap.

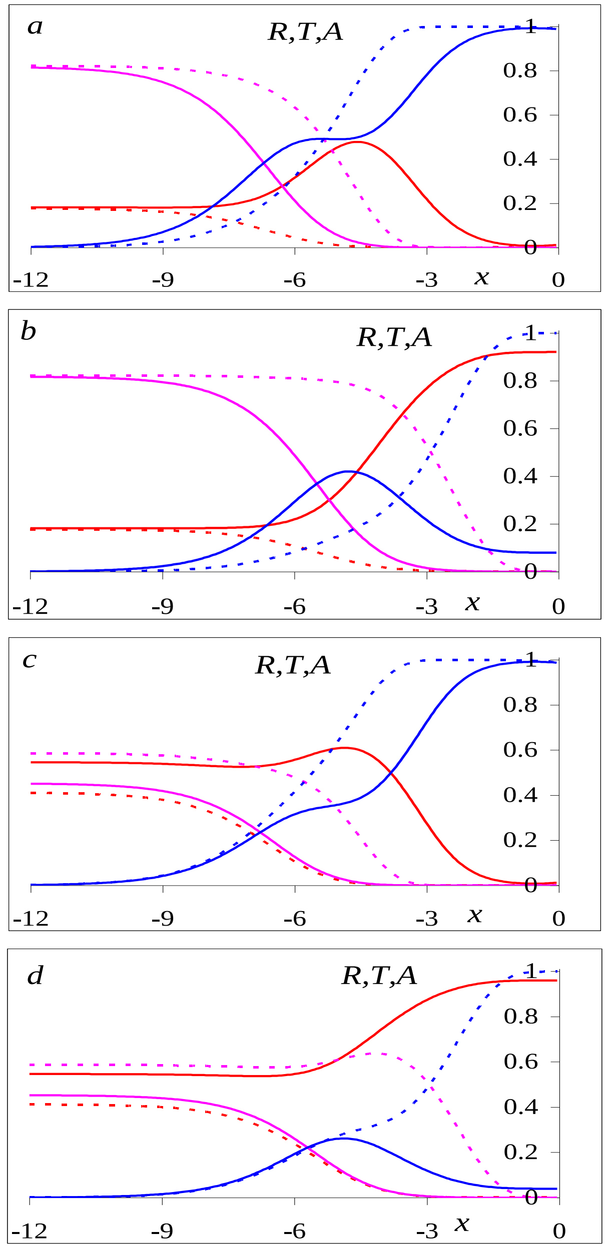

Fig. 4. The dependences of the reflection (the red lines), transmission (the pink lines) and absorption (the blue lines) on $x = \ln(\mathrm{Im}\,\varepsilon_m)$. The solid lines correspond to the right circular polarization of the incident light and those dashed to the right circular polarization. *a*,*c*: $n_o'' = n_e'' \neq 0$ and $n'' = 0$; *b*,*d*: $n_o'' = n_e'' = 0$ and $n'' \neq 0$. *a*,*b*: d_2=2100 nm, λ=617.5 nm, *c*,*d*: d_2=2000 nm, λ=625.5 nm.

As x increases, transmission decreases, but for the incident light with the right diffracting circular polarization – due to diffraction interaction of the light with the system – it takes place much more quickly than that for the left circular polarization. Furthermore, in the case, $n_o'' = n_e'' \neq 0$ and $n'' = 0$, the transmission decrease takes place earlier – as a result of the essential absorption in the first sublayer of the CLC – than that in the case, $n_o'' = n_e'' = 0$ and $n'' \neq 0$. The above mentioned peculiarities of the circular dichroism are explained in this way.

Note the decrease of the light energy in the system (the decrease of A) after passing the peak for the incident light with the right circular polarization if x is increasing. Also note one more unique effect, namely the increase of the transmission for the incident light with the left circular polarization if x is increasing (Fig. 4*d*). To present the whole picture of the problem we bring the evolution of the spectra of the circular dichroism when the absorption (the parameter x) increases in Fig. 5.

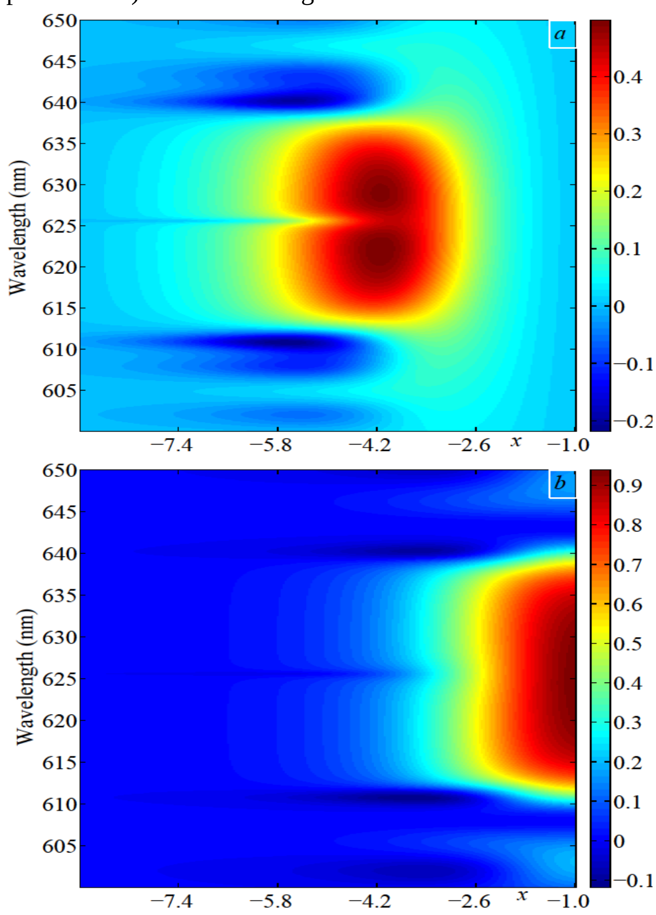

Fig 5. The density plots for the circular dichroism spectra versus x characterizing the absorption. *a*: $n_o'' = n_e'' \neq 0$ and $n'' = 0$; *b*: $n_o'' = n_e'' = 0$ and $n'' \neq 0$.

3 CONCLUSIONS

Circular dichroism peculiarities are analyzed at various eigen polarizations in multilayered one-dimensional chiral soft matter with two layers of CLCs and an isotropic defect layer inside. The sign change of the circular dichroism occurs at the defect mode. The exception is the case when the defect mode is located in the center of the photonic band gap. Our study display interesting non monotonous behavior of the circular dichroism under variation of x. When there is absorption only in the CLC sublayers, the circular dichroism first decreases, reaches minimum, then increases to its maximum, then decreases and vanishes as x increases. However, if there is absorption in the defect layer, the circular dichroism firstly decreases reaching a minimum, then increases and tends to the unit as x keeps increasing. density of states shows that when gain

Finally, the design principles outlined in this paper, which combine the concepts of a finite CLC layer with an enclosed isotropic (defect) layer, represent a model for simulation of the properties of a more complex multilayer (periodic or non-priodic) cholesteric soft matter structures. The working principle includes tunable optical chirality of the multilayer micro fluidic system, polarization and its rotation due to the change of the liquid in the micro channels. Also, due to the intrinsic characteristics of absorption and gain, our study opens avenues for the design of novel responsive materials and devices over a wide range of length scales. In particular, recent developments in micro scale fabrication open exciting opportunities for miniaturization of the proposed structures, with potential applications ranging from tunable metamaterials to switchable optics.

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